NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN INVESTIGATION INTO THE
SOOT PRODUCTION PROCESSES
IN A GAS TURBINE ENGINE

by

Alan L. Lohman

September 1984

Thesis Advisor: D. W. Netzer

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An Investigation into the Soot Production Processes in a Gas Turbine Engine

by

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ABSTRACT

This thesis details an investigation into the nature of soot production in a gas turbine combustor. The goal was to obtain axial temperature profiles and soot size distributions inside an Allison T63-A-5A combustor. The present temperature probe and gas sampling apparatus were able to acquire data. Results from these initial tests suggested some preliminary conclusions. First of all, flatter temperature profiles were possibly indicative of fuels with lower aromatic content. Also, soot size along the centerline of the combustor did not appear to change appreciably. Soot itself seemed to be composed of 0.1 micron spherical particles prone to agglomeration. Relatively large, puff-like structures observed on sample collection filters were apparently artifacts of the sampling technique. Several methods of improving the apparatus were suggested.

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I. INTRODUCTION

The aircraft of the United States Navy constitute one of the larger air forces in the world. Certainly then, the Navy has a vested interest in obtaining peak performance from the engines which power these craft. The dominant engine in modern aircraft is the axial flow gas turbine and its various derivatives (turboshaft, turboprop, turbofan and turbojet). One element of turbojet performance is combustor generated soot.

Consideration is being given by both the civillian sector and the military to the use of alternate, or wider specification fuels. This is necessary in order to anticipate the effects of world events and supplies on the quantity of available crude for production of JP-4 and JP-5. In addition, smoke suppressant fuel additives are being used in some engines when they are operated in test cells after overhaul; the use of such additives sometimes being the only practical way to meet local ambient air quality standards. The effects of alternate fuel compositions and additives needs to be determined. The formation of soot, NOx and other pollutants, as well as metallic deposits are all effected by the fuel being burned. These factors can effect aircraft combat survivability, hot-section performance, and engine life. Current technology has not yet produced a high performance engine that is soot-free between overhauls. Before such an engine can be produced the soot formation/consumption processes will have to be more clearly understood.

Gas turbine combustion research at the Naval Postgraduate School has centered on evaluating smoke suppressant fuel additives and alternate fuel compositions.

This research has been in support of the Navy's Aircraft Pollution Abatement Subproject.

Some of the earlier research performed at the Naval Postgraduate School concerning smoke suppressant fuel additives was conducted by Bramer [Ref. 1]. Various parameters were measured and correlated for six different fuel additives. While this research identified some effective additives, it was limited in scope. A simulated ramjet-type dump burner had been used and measurements were made only in the exhaust stack.

Subsequently, Krug [Ref. 2] and DuBeau [Ref. 3] constructed a full scale gas turbine combustor test facility. This facility incorporated the combustor from an Allison T63-A-5A engine. Krug and DuBeau conducted initial operations to check out the combustor and the associated diagnostic equipment.

Weller [Ref. 4] then used this apparatus to examine the effects of fuel composition and additives on exhaust NOx concentration and aft-combustor section soot size. The latter was determined using light transmission measurements through the combustor.

This thesis documents evaluations of various fuel compositions made using the full scale gas turbine combustor test facility. Several modifications were made to the existing test apparatus before these evaluations could be made. A probe traversing mechanism was developed to obtain measurements along the axis of the combustor. When used with a thermocouple probe, axial temperature profiles were obtained. The same mechanism held a gas sampling probe to measure soot particle size/concentration distributions along the centerline. Other modifications included re-routing all control lines so that tests were operated completely from the control room. Also, a flow meter was incorporated for more accurate fuel flow measurements. A Technical Heater

gas analysis sampling hose was used to help prevent condensation when obtaining soot samples. Finally, a new high capacity air compressor replaced the old unit.

The goal of the present study was to investigate how the axial temperature profiles and the soot particle size/concentration distributions varied with different fuel compositions and fuel-air ratios. A shorter term goal of the NPS effort has been to evaluate new smoke suppressant fuel additives that the Navy can use in its test facilities. The longer term goal has been to obtain a clearer definition of the soot production and consumption process inside a combustor. With a clearer understanding of sooting processes, smoke suppression could be accomplished through combustor design and/or tailored additive compostion.

II. EXPERIMENTAL APPARATUS

A. GENERAL DESCRIPTION

This investigation used the same equipment as used by Krug, DuBeau, and Weller, with some modifications. A detailed description of their apparatus can be found in Refs. 2, 3 and 4. For completeness, the following is a description of the equipment set up for the current investigation. This description incudes all the incorporated changes. The apparatus included a gas turbine combustor, an air supply system, a fuel system, a traversing probe holder, two different probes, and the associated control and data recording equipment.

B. COMBUSTOR

The combustor used was taken from an Allison T 63-A-5A engine. The section from the engine included the ignitor, the combustor housing, the combustor liner, and the turbine nozzle blocks. This section was mounted on a static test stand (Fig. 1). A stainless steel exhaust chamber was added aft of the nozzle block. This aft chamber had five holes in it. Four of the holes were for exhaust gas, and were dimensioned to provide the desired combustor pressure. Exhaust pipes were welded onto these holes to divert the exhaust flow away from the probe holder/traversing mechanism. The fifth hole was through the centerline axis of the combustor. This hole allowed for the insertion of measurement probes (Fig. 2) and incorporated a bushing seal.

C. AIR SUPPLY

Since the combustor had been removed from the engine, air had to be compressed and supplied from a separate system. A Bauer, Model IFS-34, compressor was used to compress the air which was stored in several large tanks at approximately 3000 psi. The Bauer compressor replaced the Joy Manufacturing model which had been used previosly. The air was supplied through piping to the two combustor inlet ducts. This was the same point where the original engine air supply entered the combustor.

Fig. 3 is a schematic of the air and fuel supply systems. It shows several manual shutoff valves for isolating various components of the system. The filter downstream of the compressor and tanks protected the other components. A dome loaded pressure regulator and a sonic choke allowed air flow rate to be controlled remotely. A solenoid operated valve allowed for on/off operation from the control room. The sonic choke, pressure tap and thermocouple provided accurate measurement of the air flow rate.

D. FUEL SUPPLY

The fuel supply system consisted of a fuel supply tank, a nitrogen tank, a flow control valve, a turbine flowmeter with an LED readout, two Eldex precision metering pumps, and an elctro-mechanical remote control panel. The remote control panel allowed the fuel tank to be pressurized with nitrogen. The flow control valve, located in the control room, was used to adjust the fuel flow rate. The LED readout of fuel flow was located directly below the valve to allow precise control. The Eldex, Model E, metering pumps could be used to provide desired fuel additive levels. These pumps were electrically driven, and were controlled from the remote control panel.

E. TRAVERSING PROBE HOLDER

The probe holder was fabricated locally in the shape of an inverted letter 'T'. Two inch thick aluminum stock provided for probe support. Two linear bearings were used in the bottom of the probe holder. The bearings rode on two steel rods, creating a very rigid structure with only one degree of motion (Fig. 2).

Motion was achieved by pushing the probe holder with a pneumatically driven rod. A pneumatic actuator was fixed to the test stand. The actuating rod was bolted to the probe holder. Controlled by a valve in the control room, 100 psi nitrogen was used to drive the actuator. A linear potentiometer was also connected to the probe holder. This provided a voltage proportional to probe displacement.

F. PROBES

Two different probes were used in this investigation. These were the same two probes developed by Krug and DuBeau, although they were shortened in order to be used in the probe traversing mechanism. One probe was for stagnation temperature measurements, and the other for gas sampling. Collecting gas samples required the use of a particulate collection apparatus, in addition to the sampling probe.

1. Temperature Probe

The stagnation temperature probe consisted of a chromel-alumel thermocouple surrounded by a water cooled jacket. The thermocouple was inserted to near the tip of the probe. The tube was sealed using high temperature cement. The water cooling was to protect the probe and did not significantly effect the temperature measurement.

2. Sampling Probe

The gas sampling probe was designed to remove a sample of the combustion product from the combustor under isokinetic conditions. "Isokinetic conditions" meant that the flow rate through the probe was the same as that outside the probe. The sampling probe had static pressure ports both on the inside of the probe and on the outside of the probe in order to accomplish isokinetic sampling. Additionally, the probe was water cooled to protect it. The water used for cooling was approximately 70°F. This probe also had provision for a nitrogen quench of the sample, as well as an output to a NOx analyzer.

3. Particulate Collection Apparatus

From the probe the sample went to a portable laboratory oven via a three foot section of Technical Heater, Incorporated, Model LP212 Heated Gas Analysis Sampling Hose (see Fig. 1). Inside the oven the probe gases were bypassed until isokinetic conditions were established. Two solenoid operated valves then directed the gases through two Swin-Lok Membrane Holders mounted in series. Inside the first holder was a 8.0 micron nucleopore filter; inside the second was a 0.2 micron filter. Simultaneous with the operation of the solenoid valves, a timer was started to measure sampling time. Particulate size was determined by analyzing the filters with a Scanning Electron Microscope (SEM). Soot concentration could be determined by weighing the filters before and after a test.

Downstream of the filters was a restritor valve and a flowmeter. Isokinetic conditions were achieved by adjustment of the restrictor valve until there was no difference between the static pressures inside and outside the sampling probe. Static pressure difference was

monitored on a voltmeter connected to a differential pressure transducer.

G. CONTROLS AND DATA RECORDING

Controls were placed such that the entire operation could be run from the control room. Controls for the fuel system included a control valve and pressure gage for setting nitrogen pressure in the tank, and a vent switch for relieving pressure. A fuel shut-off switch was located next to the ignitor switch on the main control panel. Above the control panel was a flow control valve for adjusting the fuel flow. On the air supply there was a control valve for setting the pressure in the air line, and a switch to open and shut the air supply electronically.

Probe travel was managed with a metering valve which controlled the rate of nitrogen flow to the probe's pneumatic actuator. Particulate sampling was controlled by a single control which diverted flow through the sampling filters and activated the sampling timer. The restrictor valve on the sampling line was used to establish and maintain isokinetic conditions.

Certain critical parameters were recorded for each run. Stagnation pressure in the air supply line and pressure in the combustion chamber were recorded on a Visicorder. Stagnation temperature in the air supply line and in the exhaust chamber were recorded on strip charts. Axial temperature profiles were made on an X-Y plotter. The X input was probe positon, and the Y input was stagnation temperature from the probe. Records of the particulate samples were simply the SEM photgraphs.

III. EXPERIMENTAL PROCEDURE

Before conducting a run, all data recording equipment was turned on and allowed to warm up. Fine calibration and zeroing was performed before the data collection runs; a quick recheck of the calibrarion and zeroing was made between each run. Prior to commencing operations, all manual shut off valves had to be opened. This included two valves on the air supply line and a valve on the fuel supply line. Then the nitrogen bottles which pressurized the fuel tank and drove the remote pressure regulators were opened. The power to all thermocouple electronic ice-points was turned on, and the probe cooling water was turned on. When obtaining axial temperature profiles, the power supply to the linear potentiometer was also turned on. For particulate collection runs the filtering paper was weighed and put in place, then the oven and heated gas sampling hose were turned on.

Before lighting off the combustor the area was visually checked to be clear and a warning horn was sounded. All recording equipment was set to operate, the main air solenoid was turned on, the ignitor was turned on, followed one second later by the fuel switch. Upon light-off the ignitor switch was released. Exhaust temperature and chamber pressure were monitored to confirm a steady state condition. At this time, if a temperature profile was being obtained, the traversing mechanism was activated. It took approximately thirty seconds for the probe to move the length of the combustor. If a particulate sample was being taken, isokinetic conditions had to first be established. The restrictor valve on the sampling line was adjusted until the voltmeter indicated no static pressure difference

between the inside and the outside of the probe. Then the sample actuating switch was activated. Sample collection lasted thirty seconds, at the end of which the sampling switch was turned off. Isokinetic conditions were monitored and maintained for the duration of the sample collection.

After data collection was completed the fuel was turned off to terminate the run. The main air switch was left on for a few seconds to clear the combustor of any residual fuel and to help cool the equipment. If a particulate sample had been taken, the filter papers were removed from their holders and placed in a dessicator. The filters were subsequently weighed, then trimmed and mounted on SEM stems to be photographed.

IV. RESULTS AND DISCUSSION

A. GENERAL

The purpose of this investigation was to obtain axial temperature profiles and soot size/concentration distributions inside a realistic gas turbine combustor using traversing probes. The ultimate goal was to combine these results to help understand the soot formation/consumption process. Additionally, the extractive probe results could be compared to those of the nonextractive apparatus used by Weller [Ref. 4], Krug [Ref. 2] and DuBeau [Ref. 3].

The fuels used in this investigation were provided by the Naval Air Propulsion Center (NAPC). Fuel compositions are detailed in Ref. 7, and summarized in Table 1. Fuels 1 and 5 had been used extensively by Weller because they contained the largest and smallest amounts of aromatics, respectively. In the 1200°F to 1300°F exhaust temperature range the transmittance of the combustion products at the aft end of the combustor was about 11% for fuel 1 and about 20% for fuel 5. This investigation concentrated on these two particular fuels since they appeared to offer the widest change in transmittance.

B. TEMPERATURE PROFILES

The temperature probe used in this investigation was the same one Krug [Ref. 2] and DuBeau had used. [Ref. 3], It had been patterned after the work of Samuelson [Ref. 5]. This was intended to be a water cooled, stainless steel jacketed, stagnation temperature probe which would endure the high temperatures and aerodynamic loads inside the combustor. During early testing this probe failed due to a

lack of cooling water. After some modifications testing was resumed. The new probe (see Fig. 4) had a thermocouple which extended out the tip of the water jacket. This tip was encased in Omega High Temperature Thermocouple Cement to the point where the thermocouple was imbedded just at the surface of the cement. It was felt this design was adequate for measuring approximate stagnation temperatures. Also, since the thermocouple was almost completely water cooled, no correction was made for radiation effects.

A summary of the test conditions is presented in Table 2. Figs. 5-8 present the axial temperature profiles that were obtained. Fig. 9 superimposes all four profiles on one graph. It can be seen that runs 1 for both fuels were made at the same flow/fuel-air conditions. Similarly, runs 2 were both at the same test conditions, but at a higher fuel-air ratio than for run 1. As expected, both fuels showed almost uniformly higher temperature profiles at the higher fuel-air ratios, but the peak temperature points moved aft. For fuel 1 the peak temperature point moved from about 4.7 inches to about 5.0 inches from the fuel nozzle. For fuel 2 the peak temperature point moved from about 5.0 inches to about 5.3 inches from the nozzle. In both cases the movement was about 0.3 inches.

The uniformly higher temperatures were due to the greater amount of fuel available for combustion. The aft movement of the peak temperatures meant that longer distances were required at the higher fuel flow rate to achieve vaporization and combustion.

All the temperature profiles along the combustor axis built slowly to their peak temperatures and then fell relatively abruptly. This indicated that the primary combustion zone ended at approximately five inches from the fuel nozzle, followed by rapid mixing and dilution.

When compared to fuel 1, fuel 5 had a lower temperature profile at both fuel-air ratios. Also, both fuel 5 profiles appeared somewhat flatter about their peak temperatures. It was possible that this flatter profile was connected to the cleaner performance (lower sooting) of fuel 5. From Table 1 it was known that fuel 5 had the lowest aromatic content of the NAPC fuels.

C. PARTICULATE COLLECTION

The original particulate collection apparatus was slightly modified during the initial testing. First of all, since the combustion chamber was pressurized to approximately six atmospheres, the vacuum pump which was installed to enhance probe flow rate was superfluous. In order to maintain isokinetic conditions, the flow in the sampling line actually had to be slowed by partially closing the control valve with the vacuum pump removed. Near the fuel nozzle the valve had to be almost completely closed, and the flow rate was negligble. A second important point is that since the sampling line was pressurized, even small leaks in the line would completely disrupt isokinetic conditions. This lead to the use of better fittings around the sample holders than had been used previously.

Isokinetic sampling was a critical condition for this investigation. If the flow in the sampling line was higher than the surrounding flow, smaller particles would be sucked into the line. The composition of the sample would be biased accordingly. Conversely, if the flow in the sampling line was lower than the the surrounding flow, the sample composition would be biased toward larger particles. The pressure transducer used to monitor isokinetic conditions was senstitive to less than 0.1 psi difference. During testing the monitor indicated isokinetic samples were in fact obtained.

There were other errors inherent in the use of an extractive probe that could not have been eliminated. These errors included compostion changes due to catalytic reactions on the probe walls (although it has pointed out that stainless steel is the least reactive tube material other than quartz [Ref. 6]), and the time-averaging characteristic of a sampling probe when used in a turbulent flame. Also, the very presence of the probe created a fluid dynamic and/or thermal diturbance to the flow.

A summary of the test conditions for the sampling runs is presented in Table 3. Runs A through D used a short sampling time of approximately 30 seconds to minimize the soot collected. The purpose of these tests was to obtain particle size data, not soot concentration levels. Runs E and F were made with longer collection times in order to obtain the concentration data. These latter runs resulted in large amounts of soot, which precluded the use of the scanning electron microscope for measuring particle size. The filter membranes were weighed before and after each run in order to determine the weight of the sample collected. For the 30 second runs (A-D) the weight changes were often negative, probably due to some of the filter was being cut off by the holder or possibly oxidizing when exposed to the hot sample stream. For this reason no sample weight data are presented for runs A through D. Two 3 minute runs were made in an attempt to gather a large enough sample to weigh. These two runs (E and F) were repeats of runs A and D. Run F collected only a neglible amount on the 8.0 micron filter. This was consistent with the earlier run and the fact that this sample was collected so close to the fuel nozzle. Unfortunately, an amount of viscous black fluid was found in the probe holder upstream from the 8.0 micron filter. Thus, the weight change for this run was suspect.

In run E a 2.7 mg. sample was collected in 179.9 seconds. This weight was divided by the collection time and the sample flow rate to yield a soot concentration of approximately 0.24 mg/liter. It should be noted that this value is only a rough estimate. No clear explanation of the earlier negative weight changes has been found, so the weight change for run E is only approximate. Also, the sample flow rate was measured in the control room and had to be corrected for the temperature and pressure effects inside the combustor. The measured chamber pressure was used for the pressure correction. For the temperature correction the stagnation temperature profiles for fuel 5 were used. From Fig. 9, using a position 4.375 inches aft of the nozzle and a fuel-air ratio of 0.020 yielded 1790°F.

Even though the weight change data from the short runs was not useful, some visual observations were made. First of all, to the unaided eye, all of the 0.2 micron filters looked about the same. The sample from run B was possibly a little darker than the others. The 8.0 micron filters definitely became progressively lighter as the fuel injection point was approached (run A to run D). In fact, the sample for run D was barely noticable. It appeared that the smaller particulates which passed through the 8.0 micron filter to the 0.2 micron filter were evenly dispersed throughout the combustor. However, the soot concentretion definitely increased with distance from the fuel nozzle.

Figs. 10-19 are SEM photographs of the sampling filters. In samples A,B and C large "puff" like shapes can be seen on the 8.0 micron membranes. Sample D was the only one that lacked any of these structures. These structures were either spherical or appeared as several spheres combined in chains. The individual spheres were about 25 microns in diameter. Under higher magnification these larger spherical shapes were seen to be agglomerates of millions of smaller

particles. The SEM photographs of the 0.2 micron membranes revealed that the smaller particles were spheres that formed into larger agglomerates. The small spherical particles were about 0.1 micron in diameter. The photographs of these particles looked the same for each sampling location. Thus, the smallest soot particles appeared to be approximately 0.1 micron spheres, prone to agglomeration to larger size throughout the combustor. This was consistent with Weller's [Ref. 4] optically measured diameter of 0.2 to 0.3 microns. Weller's slightly larger number could be attributed to the agglomerates, a few of which in a large population of 0.1 micron particles would yield an average in the 0.2 to 0.3 micron range.

The large 25 micron spheres seemed to be associated with the extractive probe sampling technique. Similar structures were observed by Samuelson [Ref. 5]. He had obtained these puff-like structures when using high overall sample transport temperatures and lower cooling rates. A different morphology had been observed when using higher cooling rates. This second morphology was a plate-like structure. Samuelson had concluded that the plate-like structure had been caused by water condensation in the sample; the puff-like structures showed only slight evidence of any moisture. Based on these results, water condensation was not considered to be a problem in the present investigation, even though nitrogen dilution was not used and the probe cooling water was at 70°F.

Samuelson [Ref. 5] also suggested a scenario for the formation of the puff-like structures. A mixture of soot particles entered the probe, possibly still undergoing pyrolysis. In the probe the mixture was slowly cooled, which promoted the formation of long chains of aggregated spheroids. Some of these chains deposited across the pores of the filters. The chains built up and eventually clogged

the pore. This scenario explained the existence of puffs of roughly the same size as the filter pores. It may also explain the results obtained in the present investigation, even though the puffs were now three to four times bigger than the filter pores.

Figs. 18 and 19 suggested a possible way of eliminating the puff-like structures if only particle size data are desired. The 8.0 micron membrane from run D did not exhibit any of the 25 micron, puff-like structures. Although run D lasted for 30 seconds, it had a very low flow rate. The number of particles which entered the probe had to have been much lower than in other runs. Thus, the puff-like structures could possibly be eliminated by shorter sampling times.

V. CONCLUSIONS AND RECCOMMENDATIONS

Through some modifications and additions, the gas turbine combustor research facility at the Naval Postgraduate School has become a versatile research tool. The data obtained in this investigation indicated that the temperature probe was capable of obtaining temperature profiles without sustaining damage. The particulate collection apparatus could also be used to obtain data inside the combustor. The entire system has been improved so that a given set of test conditions could be easily and reliably acheived. The new air compressor greatly reduced the recovery time between runs.

The preliminary results of this investigation suggested a few areas for further improvement of the apparatus. The thermocouple probe should be calibrated before being extensively used in further combustor testing. More temperature profiles of various fuels could then be made to investigate the effects of fuel composition on the heat release rate. In this same vein, the fuel nozzle of the combustor might be modified to increase the vaporization rate and the mixing rate of the fuel and air.

To correct the measured sample flow rate for the temperature inside the combustor requires a knowledge of the static temperature at the sampling point. Accepting that the present temperature probe gives a valid stagnation temperature, static temperature could be calculated if the velocity at the sampling point were known. If the sample line on the sampling probe were plugged it could be used as a pitot static tube to obtain velocities inside the combustor. The readout would be on the voltmeter currently used to monitor isokinetic conditions. This procedure would

provide a more accurate sample flow rate. Another possible solution is to merely measure the pressure and temperature within the flowmeter.

The puff-like structures observed in the SEM photographs of the samples appear to be a by-product of the sampling technique. To obtain more representative samples it is suggested that sampling times of approximately one second be tried. Nitrogen dilution and the use of slower cooling rates (hotter cooling water) should still be investigated to determine if they have any effect on sample morphology. Other fuels could be tested to determine if soot size varies with fuel composition. The present investigation has indicated that soot size does not seem to vary appreciably along the centerline of the T-63 combustor.

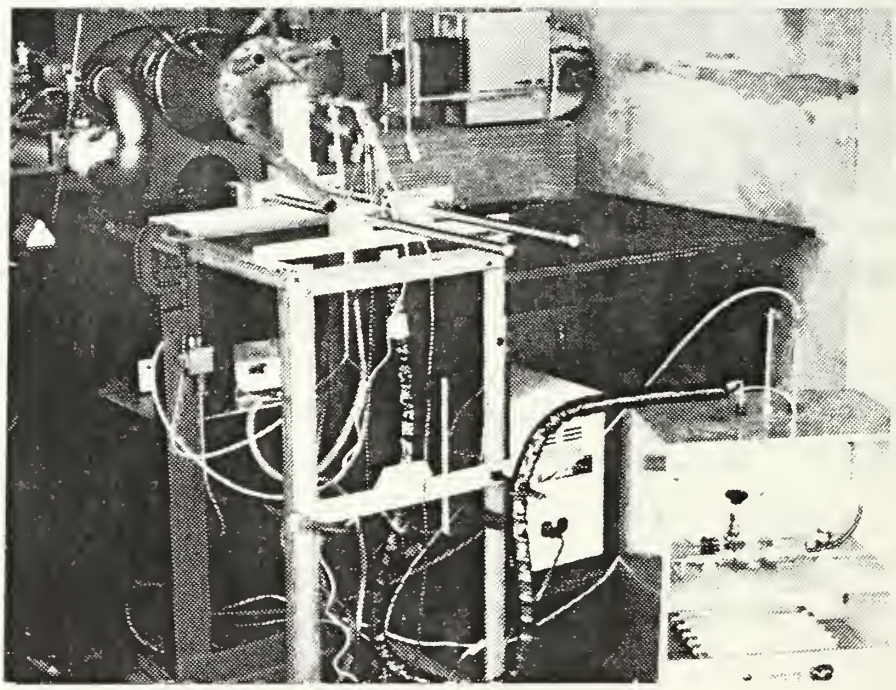

Figure 1 T63 Combustor with Sampling Apparatus.

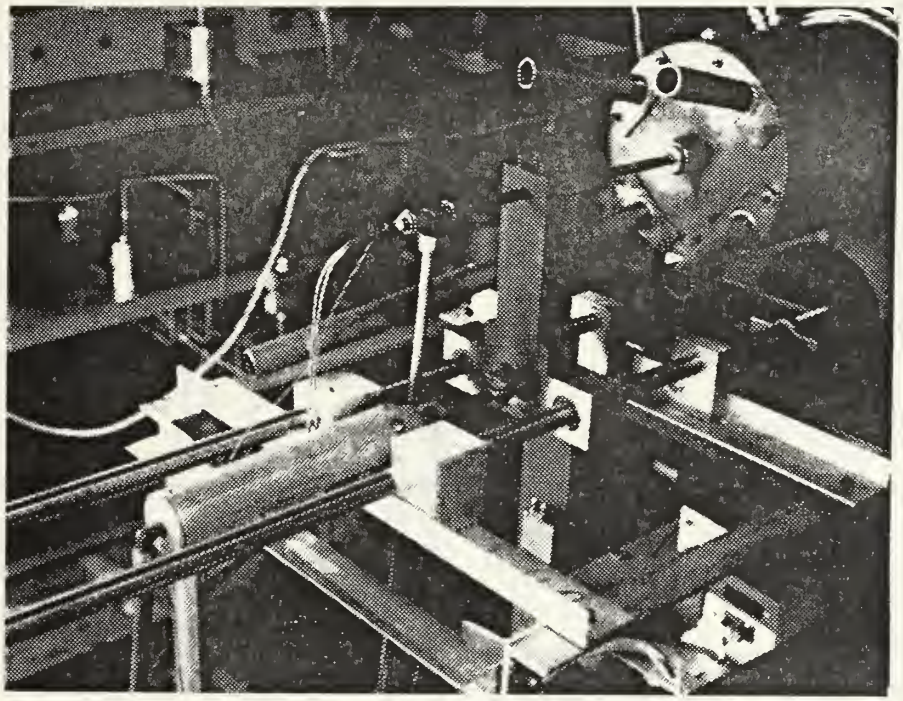

Figure 2 Exhaust Chamber, Temperature Probe and Holder.

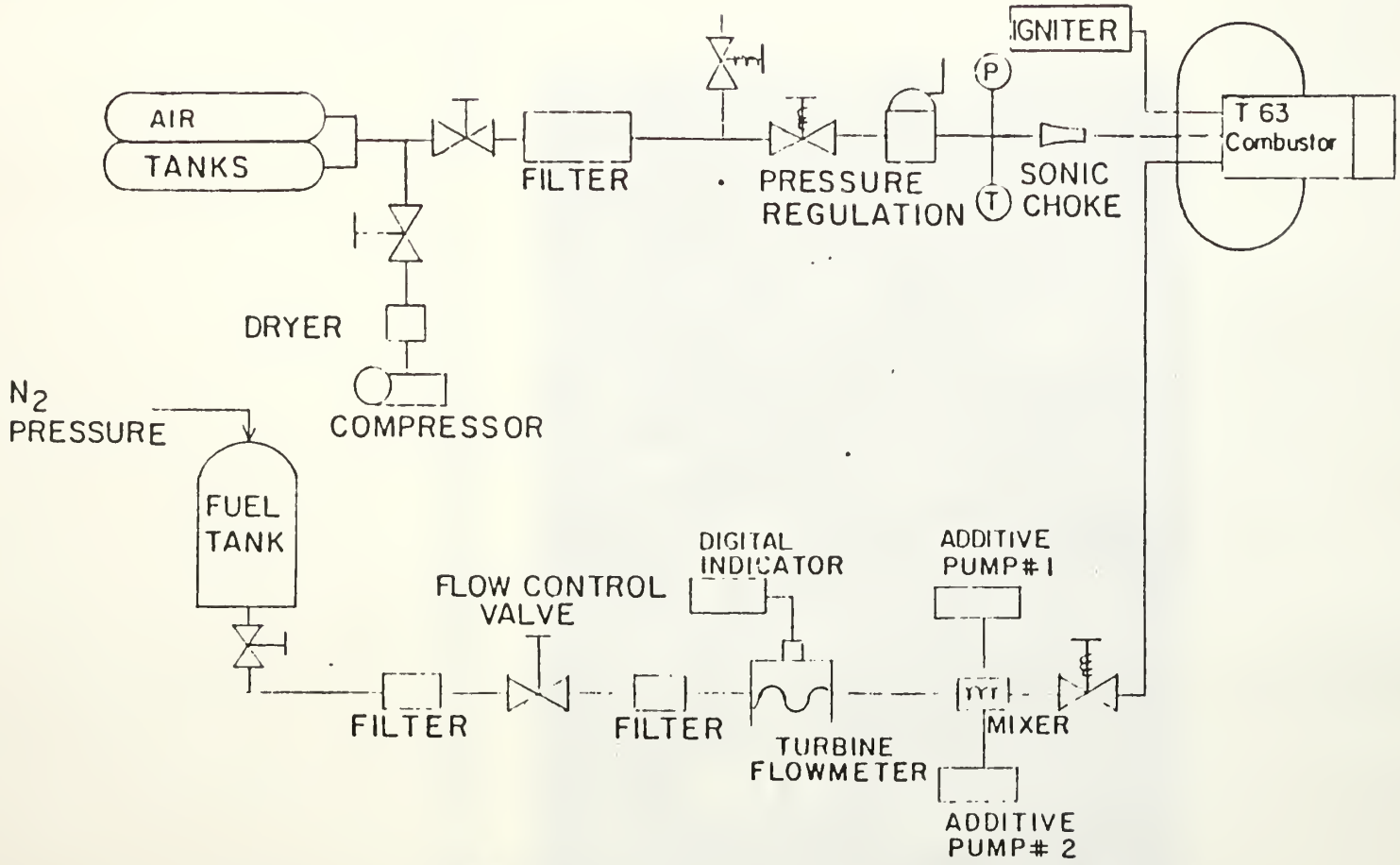

Figure 3 Schematic of the Air and Fuel Supply Systems.

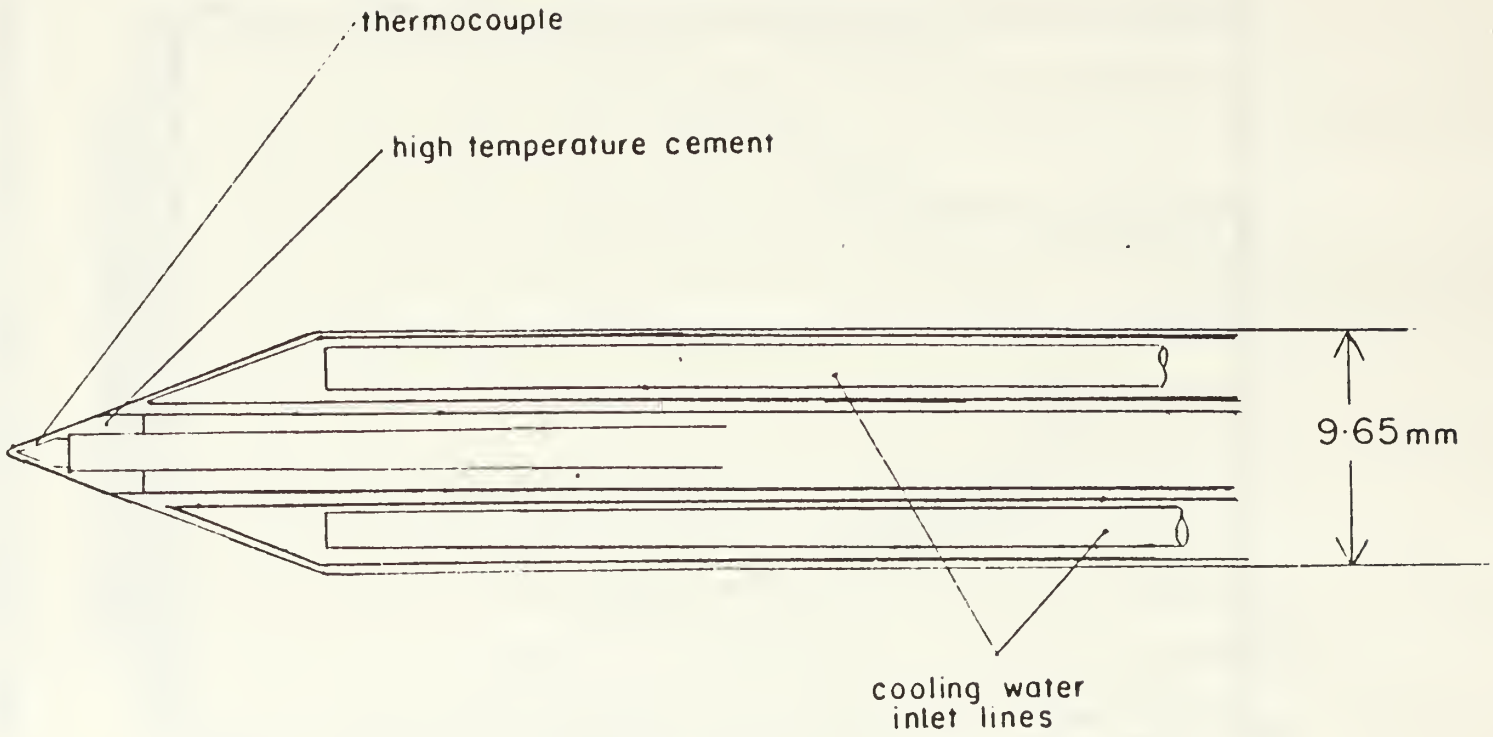

Figure 4 Schematic of Modified Temperature Probe.

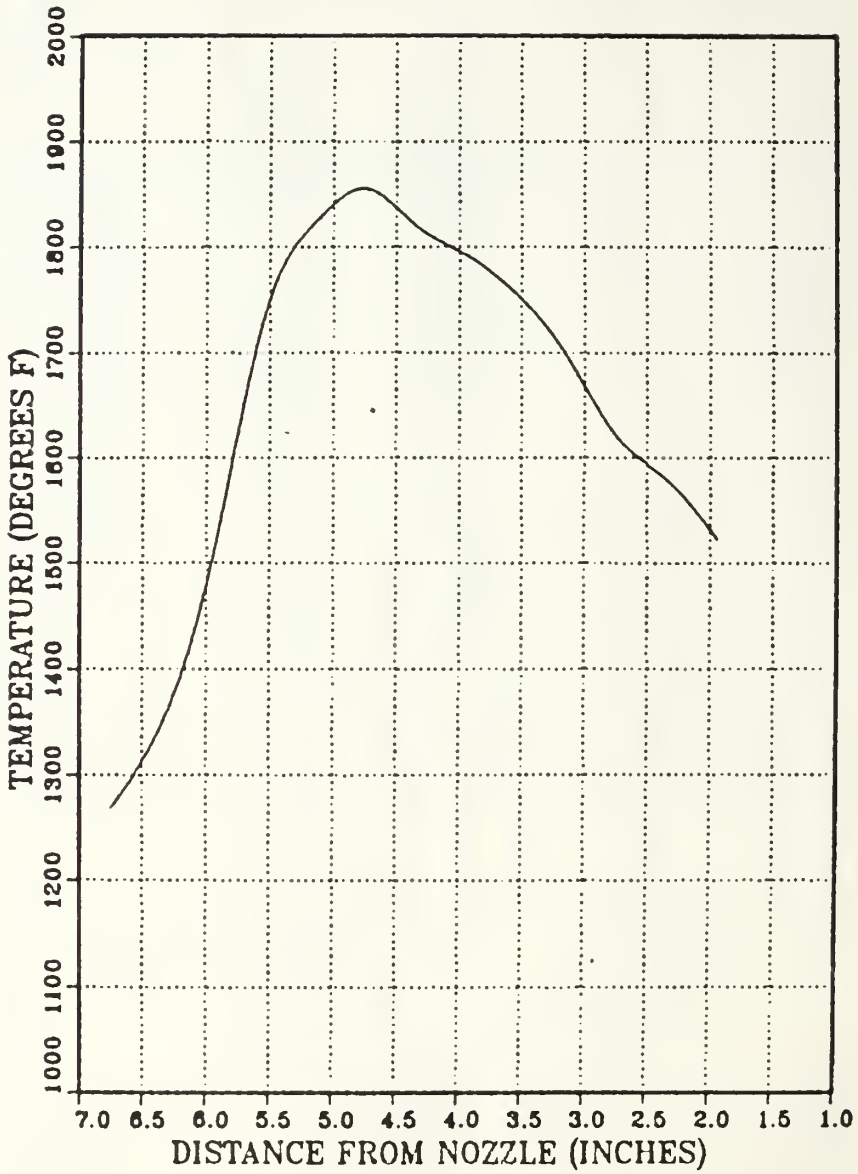

Figure 5 Temp. Profile from Run 1-1, Fuel-air Ratio = 0.019.

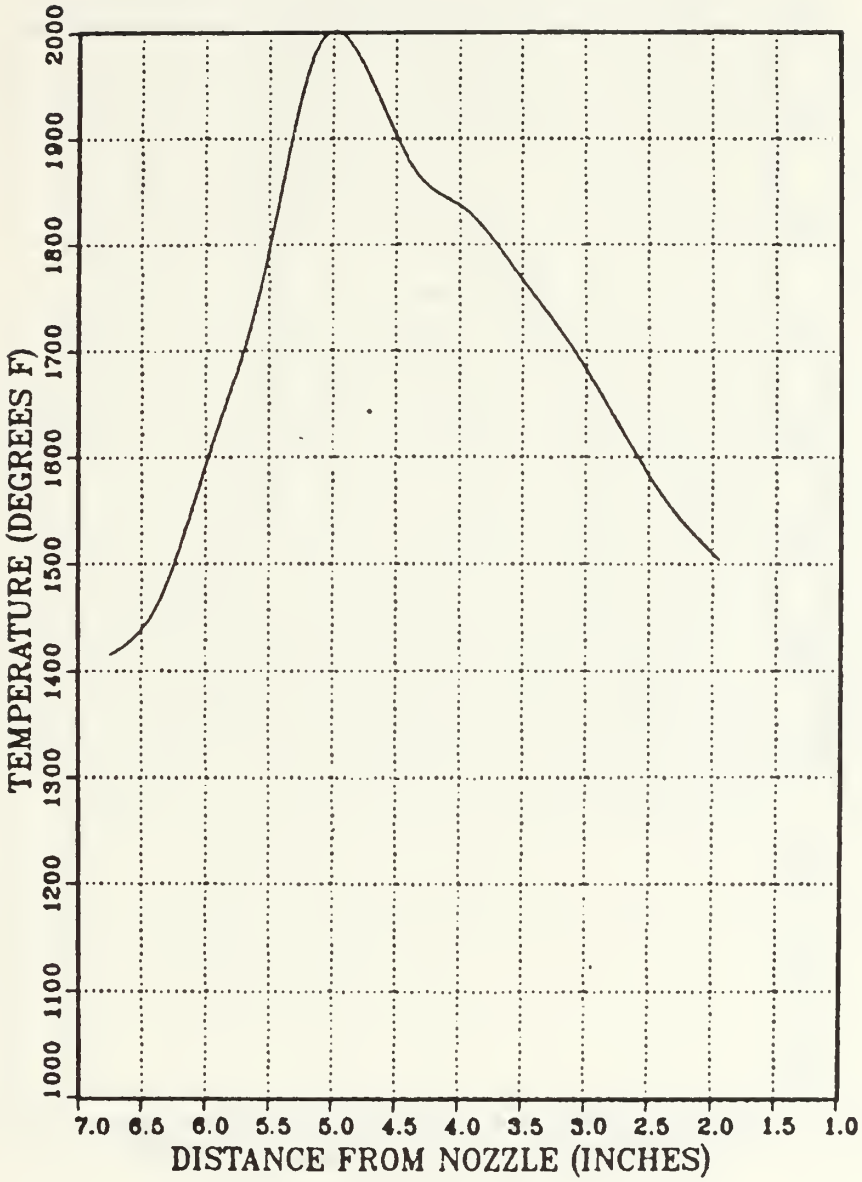

Figure 6 Temp. Profile from Run 1-2, Fuel-air Ratio = 0.021.

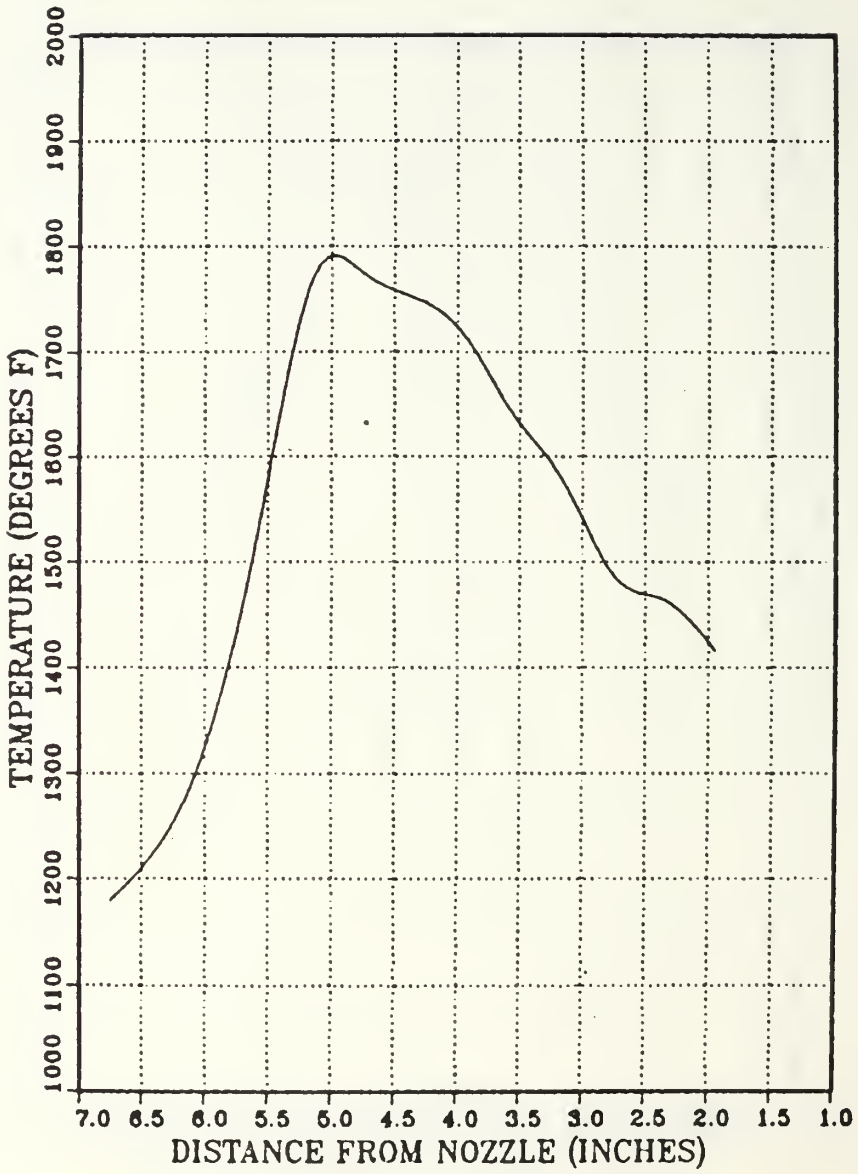

Figure 7 Temp. Profile from Run 5-1, Fuel-air Ratio = 0.019.

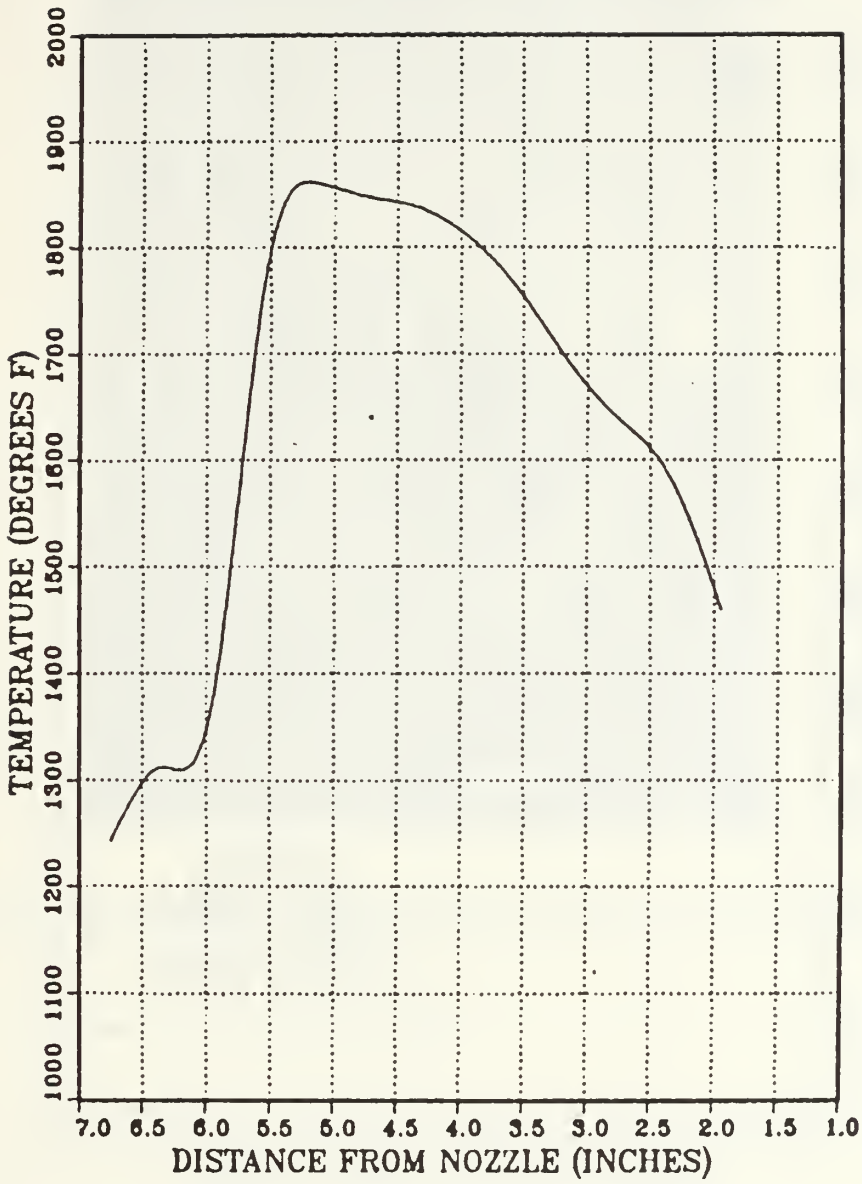

Figure 8 Temp. Profile from Run 5-2, Fuel-air Ratio = 0.021.

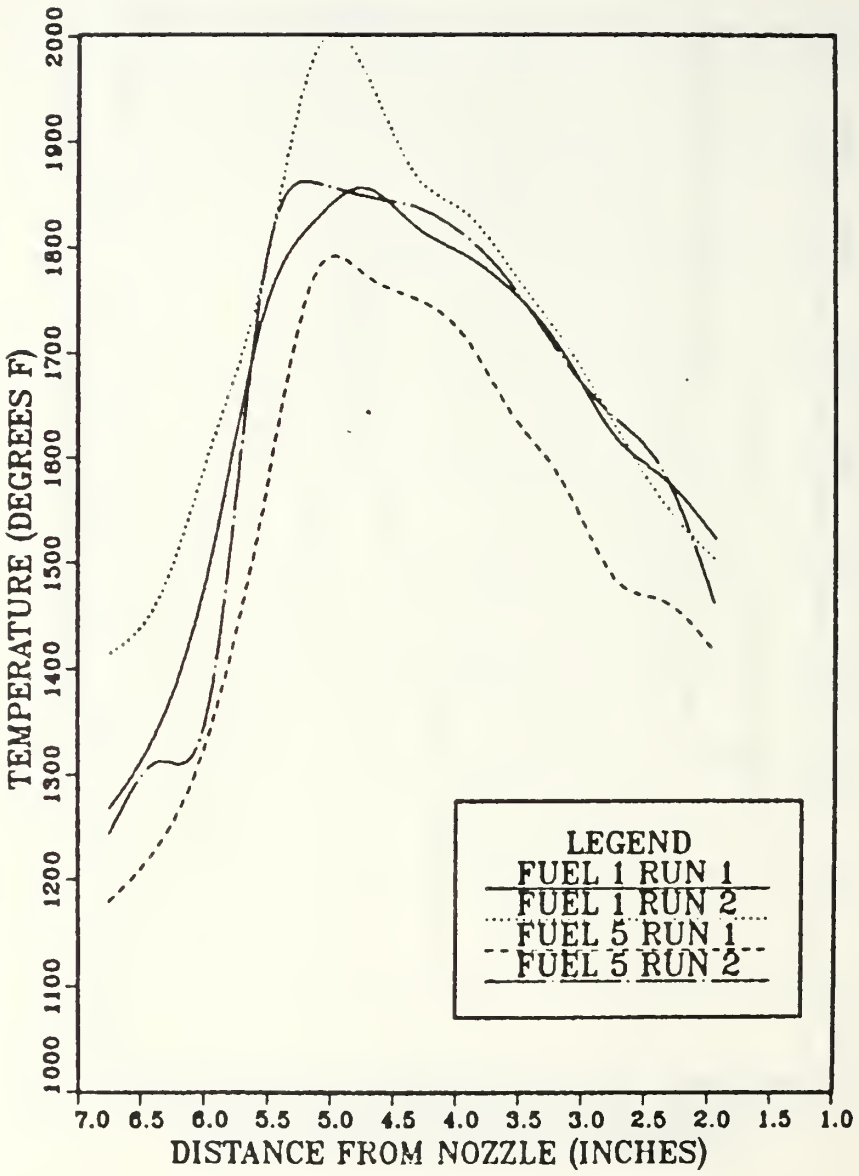

Figure 9 Temperature Profiles Superimposed.

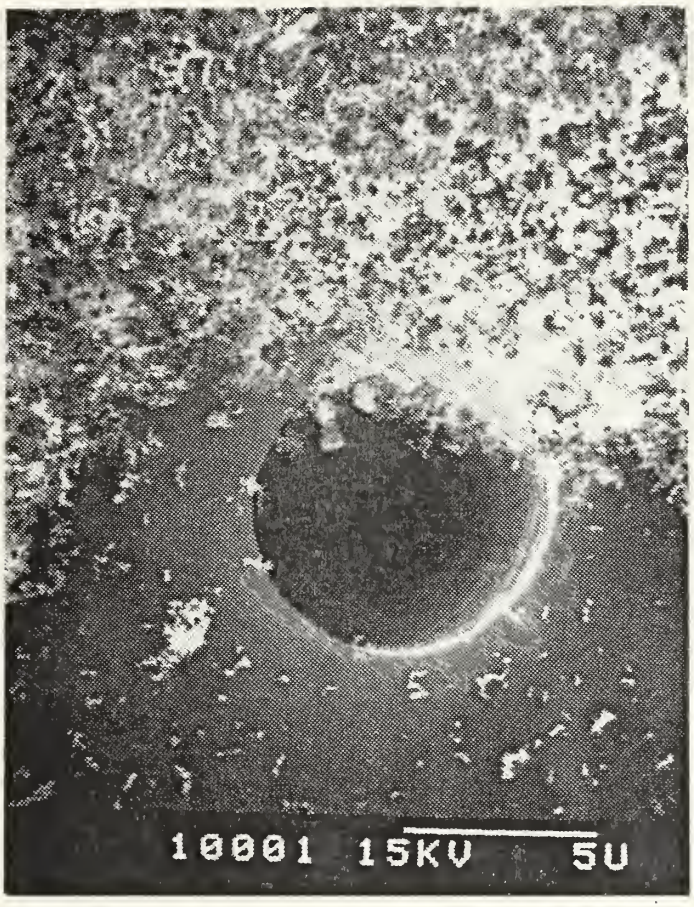

Figure 10 SEM Photo of 8.0 Micron Filter from Sample Run A.

Figure 11 SEM Photo of 0.2 Micron Filter from Sample Run A.

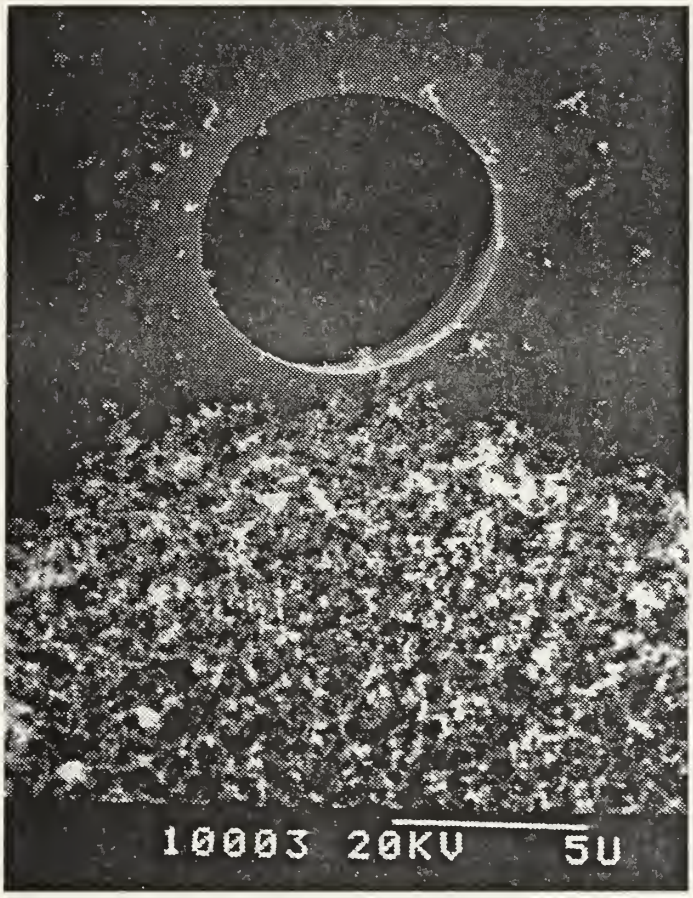

Figure 12 SEM Photo of 8.0 Micron Filter from Sample Run B.

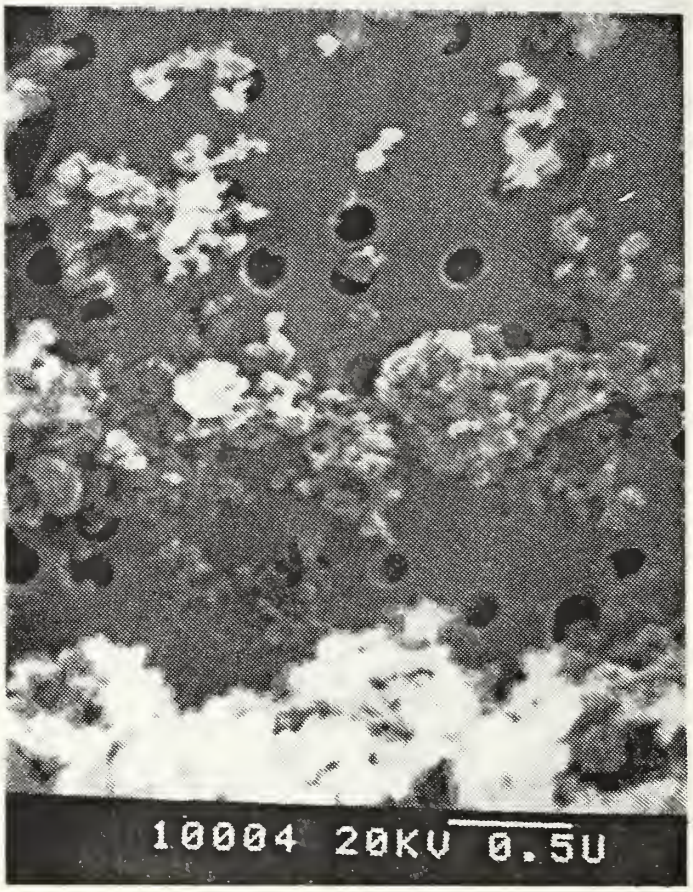

Figure 13 SEM Photo of 0.2 Micron Filter from Sample Run B.

Figure 14 SEM Photo of 8.0 Micron Filter from Sample Run C.

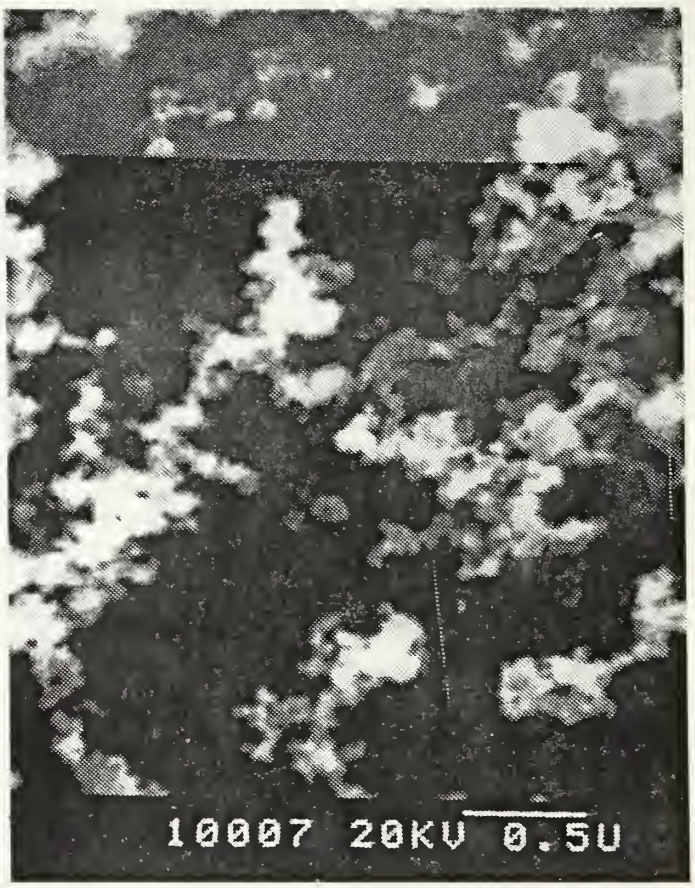

Figure 15 SEM Photo of 0.2 Micron Filter from Sample Run C.

Figure 16 SEM Photo of 8.0 Micron Filter from Sample Run D.

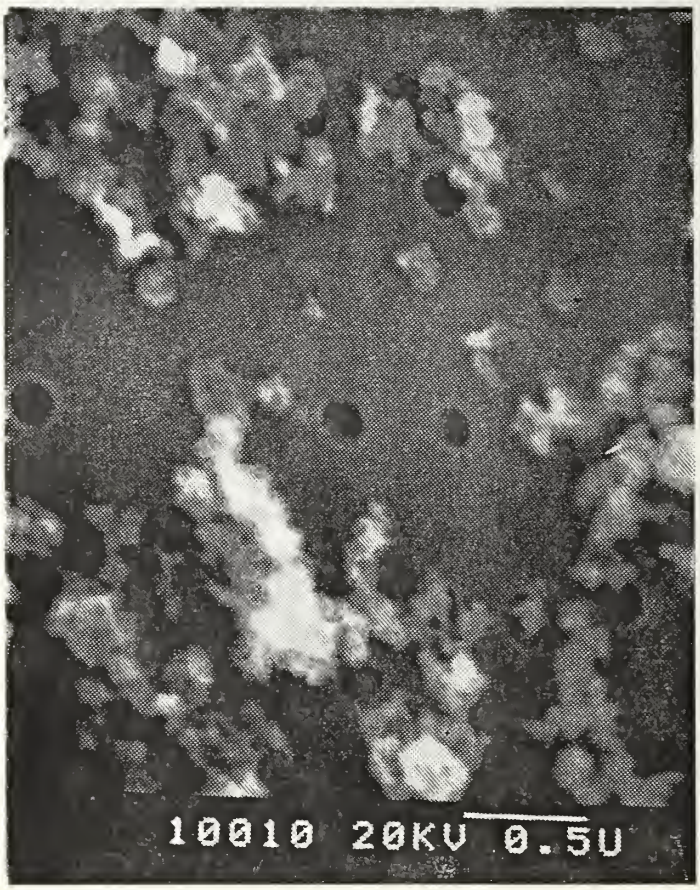

Figure 17 SEM Photo of 0.2 Micron Filter from Sample Run D.

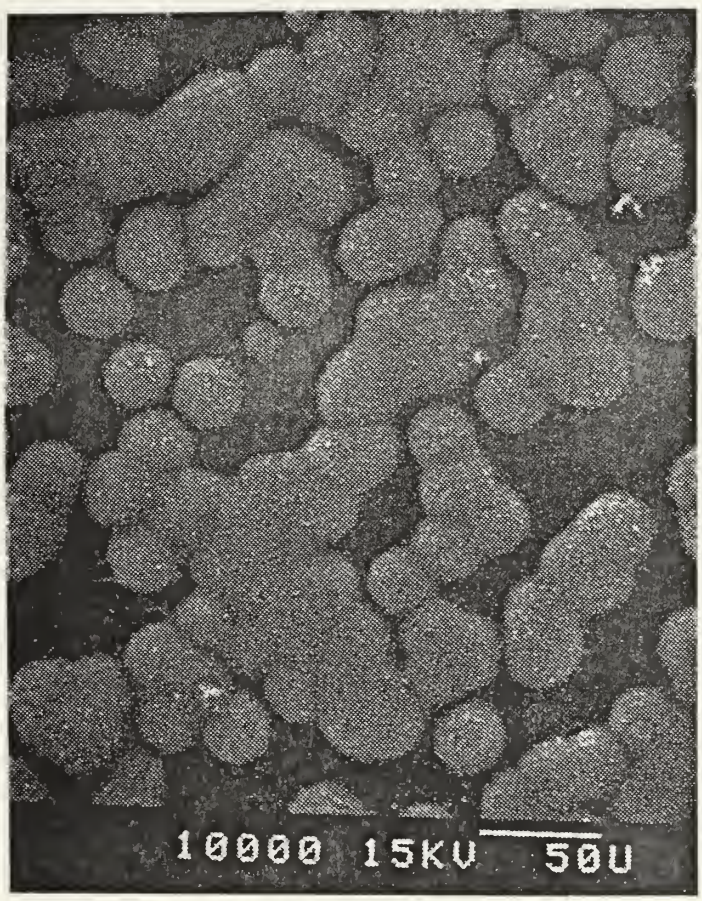

Figure 18 Run A 8.0 Micron Filter at Lower Magnification.

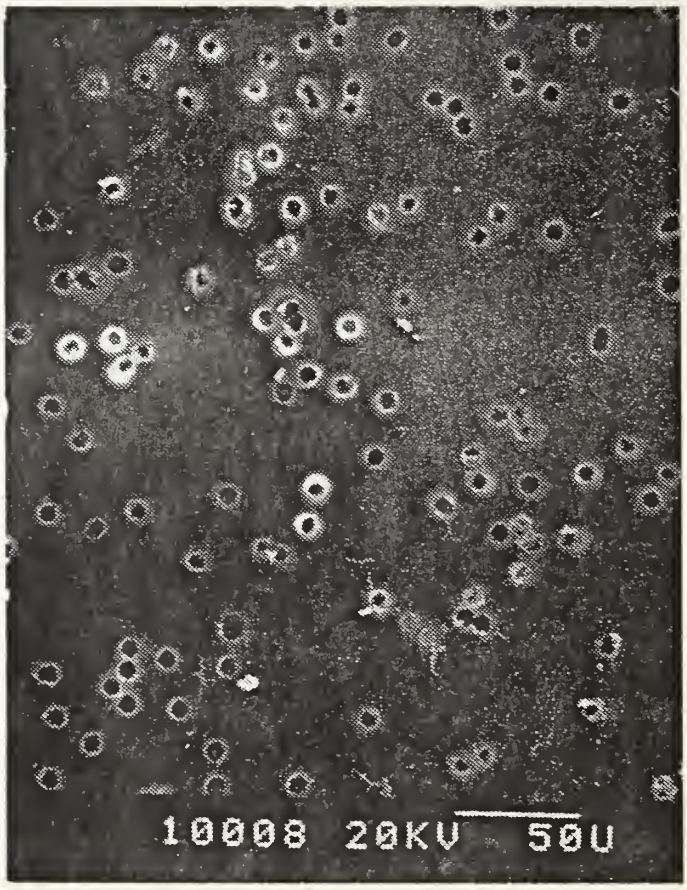

Figure 19 Run D 8.0 Micron Filter at Lower Magnification.

TABLE 1

Properties of NAPC Fuels

	1 (SUNTECH 1)	2 (SUNTECH 2)	3 (SUNTECH 3)	4 (SUNTECH 4)	5 Low Aromatic JP-5	6 Fuel Oil No. 2	7 Hydrotreated Cue Oil / JP-5	8 Diesel Fuel Marine / JP-5 So/Su	9 High Aromatic JP-5	10 Oil Shale JP-5	Specif. MIL-T-5624L Requirement
API Gravity @ 15°C	38.9	37.8	41.3	41.6	41.8	37.1	35.6	38.9	40.5	43.7	37.0-48.0
Distillation (ASTM) IBP °C	163	168	171	180	181	153	193	180	190	184	---
Recovered 10%, max.	190	227	192	202	197	218	204	204	204	193	205
Recovered 20%	207	242	203	210	203	232	209	213	208	196	---
Recovered 50%	247	257	227	228	217	266	226	237	218	205	---
Recovered 90%	276	272	261	264	243	317	272	297	246	231	---
End Point, °C, max.	297	281	276	282	261	333	288	323	264	257	290
Residue (ml), max.	2.0	1.8	1.4	1.4	1.2	2.8	3.6	2.9	1.4	1.2	1.5
Loss (ml), max.	0.9	0.2	0.1	0.5	0.2	0.0	0.4	0.0	0.5	0.4	1.5
Composition Aromatics (vol%), max.	28.5	19.8	22.8	18.6	15.9	25.0	26.4	18.6	22.7	21.8	25.0
Olefins (vol%), max.	1.79	0.81	0.75	0.79	0.79	1.40	0.86	0.70	1.62	1.60	5.0
Hydrogen Content, (wt%), min.	13.36	13.48	13.66	13.82	13.79	13.22	12.83	13.54	13.49	13.70	13.50
Smoke Point, mm, min.	17.0	18.0	20.0	21.0	21.0	17.0	14.0	16.0	21.0	21.0	19.0
Aniline - Gravity Prod., min.	5,360	5,557	5,811	6,140	--	5,661	4,254	5,648	5,471	6,022	4,500
Freeze Point, °C	-30	-24	-34	-34.5	-50.0	-3.0	-31.0	-10.5	-53.0	-49.5	-46
Viscosity @ 37.8 °C, (cSt)	1.70	2.27	1.62	1.74	1.58	2.60	1.77	2.06	1.50	1.38	---
Temperature @ 12 cSt, (°C)	-30.6	-20.6	-35.6	-31.7	-35.5	-13.3	-30.6	-23.3	-35	-34.4	---

TABLE 2

Test Conditions for Temperature Profiles

run number.....	1-1	1-2	5-1	5-2
fuel number.....	1	1	5	5
T air (degrees R).....	501	500	504	508
P air (psia).....	443	440	440	435
air flow (lbm/sec).....	2.60	2.59	2.58	2.54
fuel flow (lbm/sec).....	0.049	0.054	0.048	0.054
fuel/air ratio.....	0.019	0.021	0.019	0.021
P chamber (psia).....	120	115	106	107
T chamber (degrees F)...	1247	1403	1235	1372

TABLE 3

Test Conditions for Particulate Sampling Runs

run	A	B	C	D	E	F
fuel number	5	5	5	5	5	5
T air (degrees R)	501	508	526	522	508	513
P air (psia)	370	369	368	366	377	366
air flow (lbm/sec)	2.17	2.15	2.11	2.11	2.20	2.14
fuel flow (lbm/sec)	0.044	0.044	0.044	0.043	0.045	0.045
fuel/air ratio	0.020	0.020	0.021	0.020	0.020	0.021
P chamber (psia)	99	99	98	98	101	101
T chamber (degrees F)	1275	1299	1286	1269	1308	1269
weight change for:						
0.2 micron filter (mg)					+0.4	+0.5
8.0 micron filter (mg)					+2.1	+0.0
total (mg)					+2.5	+0.5
sampling time (sec)	30.0	30.4	30.5	30.7	179.9	180.5
sampling posistion, aft of fuel nozzle (inches)	4.375	3.375	2.375	1.375	4.375	1.375
sample flow rate (cc/sec)					57.7	---
oven temp. (degrees F)	171	171	173	173	173	168
hose temp. (degrees F)	180	180	179	181	180	180

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